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Analysis of Weak Position in Overhead line under Heavy Icing Condition by Finite Element Method

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Abstract

Transmission tower is a very important component of power system, and heavy iced transmission line has became one of the important factors against its safety and stability in China's power system these years but the transmission line designed from traditional standard can't endure the more worse environment. In this paper, for positioning the weak points of the transmission line under heavy icing accurately and providing accurate positional parameters to online monitoring devices, the strain section model is built to analysis their mechanical properties under icing and wind conditions. In proposed method, the coupling effect between tower and lines is considered, then the weak tower is picked out by strain section model that is combined with eight towers. The single one-tower-two-lines model of weak tower is built to simulate and verify the weak point accurately. Finally the better way is defined to get the location of weak structure combined with the advantages of both models.

Keywords*: tower-line model, heavy iced cover, finite element method, unbalanced tension, weak point*

1. Introduction

Icing is one of the common natural phenomenon. Freezing rain begins to ice when encountering wires and towers, and icing also happens when snow melts with the condition that the temperature remains between minus 4 and 0℃ [1]. Power transmission line plays a very important role in power system [2], damage of it would have great impact on the society. During the 2008 Spring Festival, huge disaster caused by rare freezing rain and snow happened in Southern China, causing mass destruction to power grid, which made people began to reflect the design standards of the power lines. Online monitoring device for force detection also had the attention.

Towers-lines system of transmission line is coupled system composed by towers, insulator strings and wire. With different geographical conditions, the span difference, height difference and the corner of each tower are different. Unreasonable design of transmission line, like too large span difference and height difference, will lead to tower tension imbalance. The imbalance aggravates when encountering bad weather such as strong wind or freezing, which may cause tower break, tower collapse and line fracture, making a significant impact on people's production and living [4]. At the same time, limited by the calculation conditions and construction, the installation location of the transmission line towers stress detection device can not be accurately installed in stress-concentration steel structures defined as weak points. It reduce the accuracy of tower-line system structural failure prediction.

As the mutual coupling between the insulator, tower and wire, external factors involved icing gravity, wind and etc., it is difficult to determine the initial shape of the tower-line model, and so is the numerical analysis. In literature [1] and [9], based on mechanics principles the authors used the finite element method that applyed icing load on wire nodes. Calculation of icing load is complex. Whenever the icing thickness is changed, the load on nodes will need recalculation, and there is a deviation in the result. In [14] it proposed to establish icing elements which shared nodes with wire elements on wire surface. Avoiding the complex mechanical calculations, it can easily control the icing thickness, icing heterogeneity and uneven de-icing. This paper described the relevant principles of the finite element mechanics analysis of tower-line model for transmission line. It builded up overall strain segment finite element mechanics analysis model of overhead transmission line tower line system. Through simulation, it indentify

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the structurely weak tower in strain segment. Combined with accurate analysis in one-tower-two-lines mode, the weak points in the weak tower could be positioned. Proposed method combined the analysis characteristics of strain segment model and one-tower-two-lines model, simplifing the analysis process and effectively improving the accuracy and efficiency of the mechanical structure analysis of the icing tower-line system.

2. Mechanics Finite Element Analysis Theory of Tower-Line System

2.1. Constitutive Equation

Tower mechanics analysis is structural strength issue, which meets the basic equations of elasticity. Elasticity, also known as the theory of elasticity, is mainly about the stress, strain and displacement of the object when factors such as external force or a temperature change acted on it, so as to address the strength and stiffness problems of structural or mechanical design. Since the material concerned with is isotropic, according to the theory of elastic-plastic mechanics, controlling equations included two groups of equations as follows:

Differential equations of mechanical equilibrium

$$\begin{aligned}
&\frac{\partial \sigma_x}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}+\frac{\partial \tau_{zx}}{\partial z}+X=0\\
&\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \sigma_y}{\partial y}+\frac{\partial \tau_{zy}}{\partial z}+Y=0\\
&\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \sigma_z}{\partial z}+Z=0
\end{aligned} \qquad (1)$$

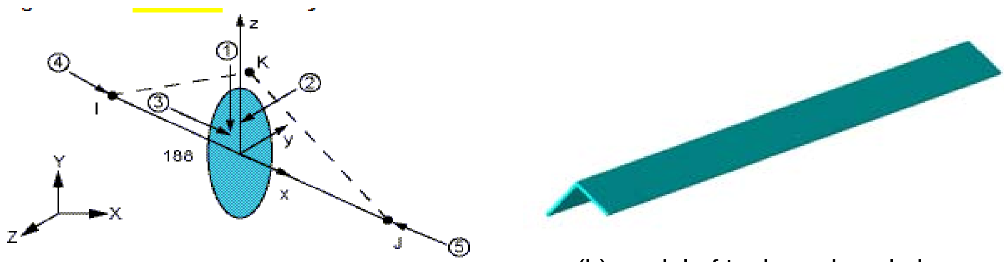
Material constitutive equations

$$\begin{aligned}
&\varepsilon_x=\frac{1}{E}[\sigma_x-\upsilon(\sigma_y+\sigma_z)]\\
&\varepsilon_y=\frac{1}{E}[\sigma_y-\upsilon(\sigma_x+\sigma_z)]\\
&\varepsilon_z=\frac{1}{E}[\sigma_z-\upsilon(\sigma_x+\sigma_y)]\\
&\gamma_{yz}=\frac{2(1+\upsilon)}{E}\tau_{yz}\\
&\gamma_{xz}=\frac{2(1+\upsilon)}{E}\tau_{xz}\\
&\gamma_{xy}=\frac{2(1+\upsilon)}{E}\tau_{xy}
\end{aligned} \qquad (2)$$

σ_x , σ_y , σ_z T_{yz} = T_{zy} , T_{xz} = T_{zx} and T_{xy} = T_{yx} of Equation (1) are stress components of different directions, X, Y, Z are the physical components of the unit volume in three coordinate directions; ε_x , ε_y , ε_z , γ_{yz} , γ_{xz} and γ_{xy} of Equation (2) are strain components of different directions, representing relations of displacement and strain of any points within the object when deformation occurs to it; E and υ represent the Young's modulus of elasticity and Poisson's ratio, meeting Hookelaw. For concrete tower-line structure system, taking the above two formulas as solving equations, based on the finite element method, we can bulid up entity model with the help of business software ANSYS [15]. It provides elelments of different types with differents degrees of freedom for modeling various structures, which would be introduced in the next chapter. We could define the properties of the material and take the the initial value of strain and direct force of sysytem as known parameter to figure out unknown variables of each node such as stress, displacement and strain. It could be used to judge the reliability of the system.

2.2. Tower Steel Structure Model

BEAM188 element is usually used on tower steel structure modeling [18]. As what is shown in Figure 1(a), it is a two-nodes-3-D linear finite strain element. It has six or seven degrees of freedom at each node, including translations in the x, y, and z directions and rotations about the x, y, and z directions and a optional degree of freedom of warping. It has the ability to withstand the tension, compression, bending, twisting and shear. Based on the Timoshenko beam theory, the plane of cross-section of the element keeps undistorted after deformation. The elastic, creep and plastic material model are supported, and also through the definition of cross-section and sectional direction defined point, cross-section simulation can be achieved. The simulation function covers a variety of materials, such as steel arch section, and is suitable for analysis of the angle bar material model of tower. As shown in Figure 1(b), by setting the real constants of BEAM188 element, we can simulate the shape and cross-section size of L-shaped angle bar.



(a) Beam188 element (b) model of L-shaped angle bar

Figure 1. 3-D Linear Finite Strain Beam Element

2.3. Wire and Ground Wire Model

As a flexible component, wire and ground wire have the characteristics that they are not subjected to bending moments or stress and only withstand tension. They can be precisely processed in accordance with the structure of the single cable. For the cross-sectional size of the cable is very small compared with the length of the cable, its flexural stiffness is so small that it can be ignored. The cable material complies with Hooke's law. Under its own weight, it has geometric shape of a catenary [9]. Compared with the general cable structures and bridges Lasso, wire and ground wire have smaller stiffness, bigger span, deflection and a higher degree of nonlinearity. The specific bilinear stiffness matrix characteristics of LINK10 element makes it a pole element which is only under pressure or tension In the axial direction. Openning the tension-only option, if the unit is under pressure, stiffness will disappear, so as to simulate the natural relaxation properties of wire and ground wire. LINK10 element has function of solving non-linear, stress stiffening and large deformation problems, making it an ideal element to analog wire and ground wire of transmission line.

2.4. Insulator Strings Model

Size of insulator strings and the wire connection fittings is much smaller compared with size of Tower-Line system, so their influnce for mechanics analysis of the Tower-Line structure is insignificant. Ignoring gravity of connection fittings and insulator strings, they can be analoged by the rigid connecting rod element LINK8. The element with two nodes and three degrees of freedom could be used for the link of tower beam element and the wire cable element.

To effectively calculate stress and deformation caused by span, height difference and uneven load of multi-span Towers-Lines system, we used BEAM188 element to analog transmission tower, LINK10 element to analog wire and ground wire and LINK8 element to analog insulator strings and connection fittings. Considering the coupling of Tower-Line system, we could create overall entity model. Beam element cross-section of the transmission tower model is "L" shaped, eccentricly connected. Wire and ground wire of transmission lines establish a cable element catenary model, and the prestress could be determined according to the installation Actinobacillus stress [15].

3. Analysis of Weak Point of Strain Segment Model of Tower-Line System
3.1. Catenary Structure

In this paper, we used the catenary formula in line design manual to simulate the wire and ground wire structure.

The 500kV overhead wires are four-split structure. To simplify the modeling process, four-split wires could be equivalent to a wire. The formulor of calculating equivalent diameter are as follows [21]:

$$d_{eq} = D\sqrt{\frac{Sd}{D}} \tag{3}$$

S is split number; D is separatist diameter; d is the diameter of the each wire.

The conductor catenary equation is as follows [16]:

$$y = \frac{\sigma_0 h}{\gamma L_{h=0}}[\sinh\frac{\gamma l}{2\sigma_0} + \sinh\frac{\gamma(2x-l)}{2\sigma_0}] - [\frac{2\sigma_0}{\gamma}\sinh\frac{\gamma x}{2\sigma_0}\sinh\frac{\gamma(l-x)}{2\sigma_0}]\sqrt{1+(\frac{h}{L_{h=0}})^2} \tag{4}$$

In the equation, the parameter $L_{h=0}$ can be calculated as follows:

$$L_{h=0} = \frac{2\sigma_0}{\gamma}\sinh\frac{\gamma l}{2\sigma_0} \tag{5}$$

l ——horizontal distance of the two suspension points;
h ——vertical distance of the two suspension points;
γ ——ratio of gravity per unit length of wire and cross-sectional area of wire;
σ_0 ——stress of the wire lowest point (the cross-section tension of wire per unit);

Coordinates of each discrete node on catenary line could be obtained according to the formula (5), value of γ is related to the wire model and value of σ_0 should be the average annual operating stress.

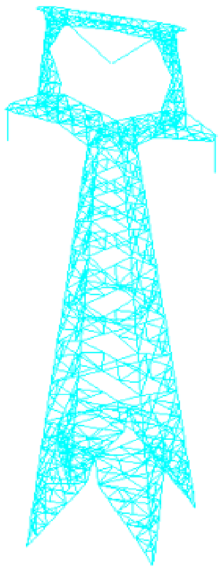
3.2. Finite Element Model of the Tower-line System

In this paper, we selected a microclimate Strain segment of a 500kV line in Central China to build up finite element model, which included 8 towers and seven spans, numbering from 182# to 189#. The 182# and 189# tower were strain towers. Considering that height difference and uneven span were of significant affect to Tower force, coordinates values of each tower in the model were taken from the actual line parameters. Each tower consisted of two kinds of steel materials, Q235 and Q345. The former one was usually used as auxiliary materials, and the latter one was usually used as main materials. Both of them have “L”-shaped cross-section, as was shown in Figure 1(b). Material parameters of the strain are as follows in Table 1.

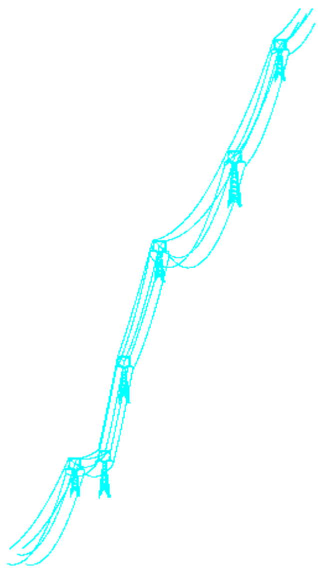
Table 1. The Physical Properties of Materials

Entity	Tower		Wire	Ground wire
Type	Q345	Q235	LGJ-400/35	GJ-80
Cross-section area (mm^2)	/	/	661.74	79.39
Elastic modulus（Mpa）	206000	206000	65000	181300
Density(t/mm^3)	7.85e-9	7.85e-9	3.1e-9	7.94e-9
Poisson's ratio	0.3	0.3	/	/
Yield strength（Mpa）	345	235	97.73	443.97

In the model, each angle bar of the tower was equivalent to an element, and the whole insulator strings were equivalent to an element. For the wire and ground wire, they were equivalent to head-tail-connected elements of 4.5 meters long according to its initial shape. There were totally 20862 elements and 14709 nodes in the finite element model of strain segment. Finite element model of Tower-line strain segment system are shown in Figure 2. Figure 2(a) is a 3-D finite element model of a typical tower used in the strain segment, Figure 2(b) is a full model diagram of the entire strain segments of transmission lines. The largest span of strain segment attains 863m, located between 184 # and 185 # tower. The maximum height difference is 61.3m, located between 186 # and 187# tower.



(a) typical single tower model



(b) strain section model

Figure 2. Finite Element Model of Transmission Line

3.3. External Force Load

Since the concerned object is mechanical properties of transmisson lines and towers, we mainly considered the effect of icing gravity and wind. According to the formula of line design manual, external force load of the model could be calculated as follows:

(1) Wind load on wire and ground wire

When the span of wire and ground wire is l_H , the wind load is calculated as follows:

$$W_x = 0.625\alpha\mu_{sc}\beta_c(d+2\delta)l_H(K_h v)^2 \times \sin^2\theta \times 10^{-3} \quad (6)$$

In the condition with icing, unit length wind load of wire produced by horizontal wind could be calculated by the following formula:

$$g_1 = 0.625\alpha\mu_{sc}(d+2\delta)(K_h v)^2 \sin^2\theta \times 10^{-3}, N/m \quad (7)$$

In the condition without icing, unit length wind load of wire produced by horizontal wind can be calculated by the following formula:

$$g_2 = 0.625\alpha\mu_{sc}d(K_h v)^2 \sin^2\theta \times 10^{-3}, N/m \quad (8)$$

In the equation, the parameter K_h could be calculated as follows:

$$K_h = (\frac{h}{h_s})^{\alpha} \quad (9)$$

h ——height from the ground or water surface to wind;

h_s ——reference height of wind speed of the lines;

α ——the coefficient related to surface roughness. For general landline it takes 0.16;

d ——diameter of wire or ground wire;

μ_{sc} ——wire shape coefficient;

β_c ——the wind load adjustment factor of wires' effect on tower in 500kV line;

v ——the prescriptive design wind speed at high baseline hs, with the unit of m/s;

K_h ——high coefficient of variation of the wind speed at the wires average height h. In condition that h is equivalten to h_s, value of K_h is 1;

δ ——wire ice thickness, with the unit of mm;

l_H ——horizontal span of tower, with the unit of m;

θ ——the angle between wind direction and wire axial.

(2) Wind load on tower

Wind load perpendicular to the surface of the structure can be calculated as follows:

$$F_t = kk_z k_T A_c \frac{v^2}{1.6} \quad (10)$$

k ——wind load shape coefficient, which is usually 1.3;

k_z ——wind pressure variation coefficient of height;

k_T ——wind load adjustment factor;

A_c ——tod win area.

(3) Icing load on wire and ground wire

Icing load on wire and ground wire per unit length can be calculated as follows:

$$g_3 = 9.8 \times 0.9 \pi \delta (d+\delta) \times 10^{-3}, \ \text{N/m} \quad (11)$$

Calculating wind load and icing load on wire and ground wire per unit length, we can calculate load on element according to the length. Deviding the load on element by two, we can get node load on two sides of element. In the same way, node load on tower element also can be obtained.

For tower foundations are deeply buried in the soil and poured with concrete, they can be considered to be rigid connection in the structure. In the finite element model, all degrees of freedom of tower foundation nodes were applied the constraints value of zero.

3.4. Strain Segment-line Model Simulation Results

The purpose of this paper is to identify structurally weak points of tower-line system through analysis of the mechanical properties of the tower-line system under the condition of icing. Considering the effect of lateral wind loads, by changing combination of icing thickness and wind speed, we can build up recyclable calculate program of the strain section to analyze force of tower-line system model. According to line design manual as well as local meteorological condition of several years, the calculation was divided into 16 groups, as is shown in Table 2:

Table 2. The Loaded Data

Group number	Icing thicknes（mm）	Wind speed(m/s)
1	0	0~30
2	2	0~30
.	.	.
.	.	.
.	.	.
14	26	0~30
15	28	0~30
16	30	0~30

Under certain climatic conditions, simulation results of displacement and stress distribution of the strain segment-line model are shown in Figure 3 and Figure 4. By calculating stress on each bar, we can obtain ratio of actual stress and yield stress, which can be used to determine instability of strain segment line-tower system. If the ratio is bigger than 1, strain segment line-tower system should be considered as failure for safe operation of power grids. Loading different combinations of icing thickness and wind speed, we could get crossover failure data of strain segment line (in the condition that strain segment line is impending structural damage).

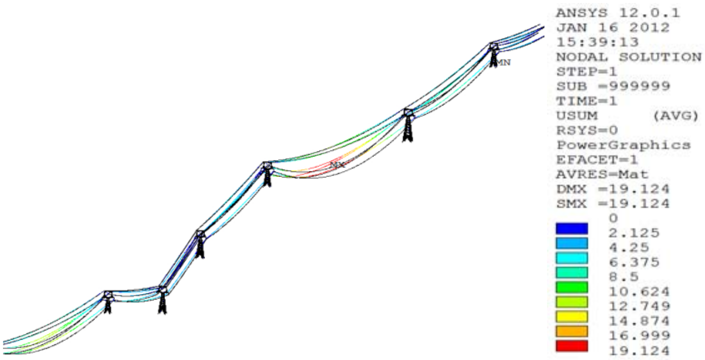


Figure 3. Displacement Distribution of Strain Section-line

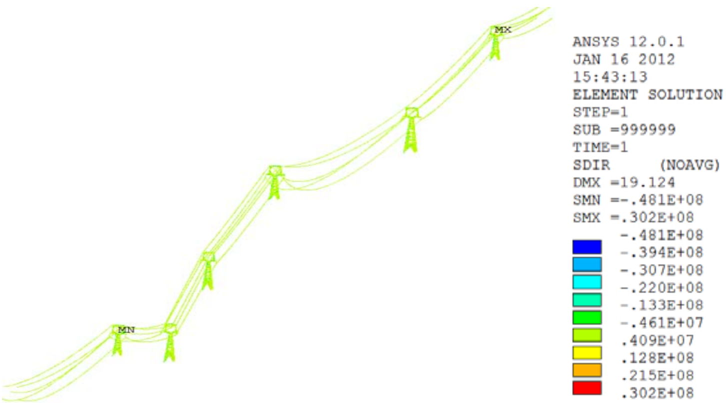


Figure 4. Stress Distribution of Strain Section-line

Table 3. The aggregation of critical failure data

Icing thickness（mm）	Wind speed（m/s）	Element num. of weak points	Tower num. of weak points	Actual stress（kN/m^2）	Ratio
12	16	8944	188#	-57933	0.1679
14	16	4641	185#	-59529	0.1725
16	12	8944	188#	-56970	0.1651
18	12	8944	188#	-58513	0.1696
20	10	8944	188#	-46276	0.1341
22	12	8944	188#	-59647	0.1729
26	14	8944	188#	-66969	0.1941
28	16	8944	188#	-71977	0.2086

Data of ice thickness and wind speed listed in Table 3 are the input loads when the tower structure was crossover failure. During the simulation process, we found out that increasing either wind speed or icing thickness of certain crossover failure data, stress of weak points listed in the table would increase a lot and exceed the yield strength of the angle bar, and in the same time displacement of nodes on the weak points was much larger than before, which meant the angle bar was structurally destroyed. This would seriously affect the safe and stable operation of the transmission lines. In the calculation of each climate condition, because the icing thickness increases 2mm or wind speed increases 2m/s, the acquired climate threshold just approximate on the real threshold and the acquired ratio was unable to be get close to 1.

As can be seen from Table 3, when the ice thickness increases, the critical value of the wind speed dose not monotonically decrease, which means critical failure icing thickness and wind speed of the strain segment line are non-linear relationship, and the trend is complex. Even sometimes when ice thickness increases, maximum wind speed that the transmisson line can withstand increase insteadly. For example, when the thickness of the ice cover increases from 22mm to 26mm, its maximum affordable wind load increases from 12m/s to 14m/s. This situation is mainly due to the different direction of the icing load and wind load which causes internal imbalance tension to offset. This partly explains why taking de-icing operations in the condition of strong wind (melting ice with DC to reduce icing thickness of the line) may cause damage to the originally stable tower-line system.

Analyzing of simulation results, we can find out that in all critical failure situations, 188# and 185# tower suffered greater stress and stress ratio. Meanwhile, among several solving process, the weak point mainly focused on element 8944 which located on the 188# tower. This means that under different climatic conditions, stress-concentrated iron bar in the strain segment is unchanged. It can come to the preliminary conclusion: for the strain segment system, 188# tower is the weak tower of the strain segment, and element 8944 located on weak tower has the most concentrated stress, and is also the weak point of the strain segment.

4. The Improved Mechanical Analysis Method of Strain Segment Weak Point

The method introduced above can used to find the weak tower and weak point, but recycled calculation of entire strain segment model would cost a lot of time. In order to work more effectively, we try to analyze one-tower-two-line model of the already found weak tower, whoes model is shown in Figure 5. In the analysis, we loaded the same limate conditions as strain segment model analysis, so as to figure out mechanical properties of 188# tower. One calculation of the one-tower-two-line model, using high-performance computer, takes 8 minutes, and to complete calculation of all conditions needs a total of 30 hours. Compared with the time cost of strain segment model of one calculation, 60 minutes, the former one is really efficient.

It can be seen from Table 4 that the maximum stress ratio occurs on element 611 in all critical failure conditions, which means the angle bar corresponding to element 611 is the weak point of one-towel-two-line model of 188# towel. By comparison, we can find out element 611 on the one-towel-two-line model and element 8944 on the strain segment model correspond to the same angle bar. In another way, weak points obtained from the two different methods are consistent.

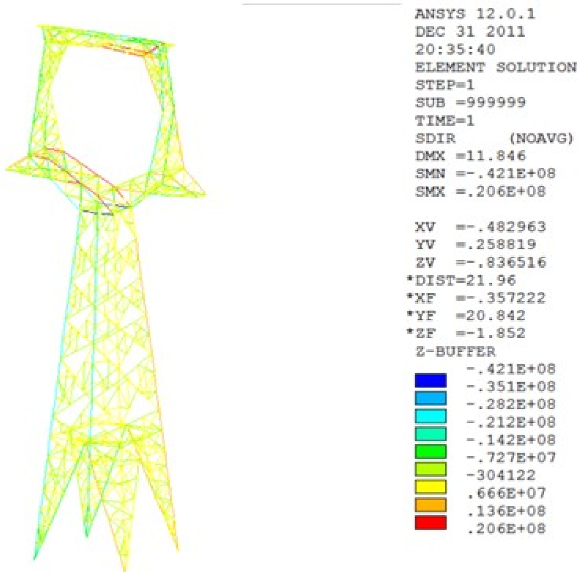


Figure 5. Stress Distribution of Weak Tower

Table 4. The Aggregation of Critical Failure Data

Icing thickness (mm)	Wind speed (m/s)	Element num. of weak point	Stress (N/m^2)	Ratio
6	20	611	-52091133	0.151
20	20	611	-45734276	0.1326
24	22	611	-47010848	0.1363
26	10	611	-55965824	0.1622
30	14	611	-52246952	0.1514

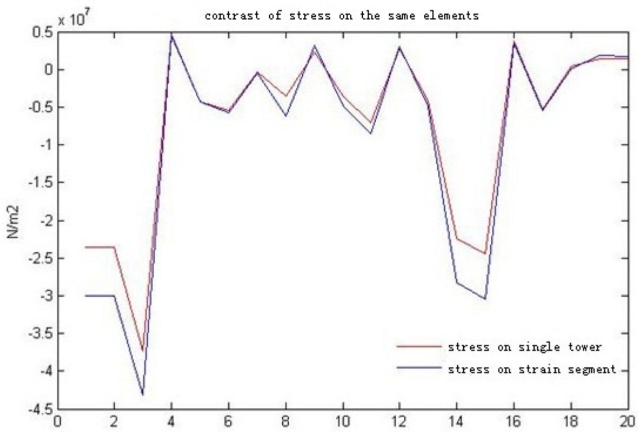


Figure 6. The Contrast Diagram between Different Models' Stress

As shown in Figure 5, compared with the strain segment result, the maximum stress ratio occurs at the same region, and the distributions of the stress concentration area are also consistent. Selecting 20 elements near the location of the element 611 where stress is concentrated to make a contrast between two models, we can find out the values of stress in two models have little difference. According to analysis above, we can conclude: results of one-tower-two-line model accurately reflect single tower mechanical properties of the strain segment model, and analysis of the former one could obtain the same results as the strain segment model.

Through above calculation of the strain segment model and one-tower-two-line model of weak tower, we acquire a kind of more effective method for positioning structurally weak point of the strain segment: Firstly calculate results of strain segment model in several climate conditions to figure out the weak tower, and then build up one-tower-two-line model of the weak tower to obtain the precise position of weak point(angle bar).

5. Conclusion

Based on study of mechanics finite element analysis on overhead line, precise 1:1 models of strain segment and one-tower-two-line systems of 500kV overhead line are established in this paper. For the maximum of wind speed and icing thickness that might occur to this certain line, mechanics finite element calculating of the models under many different conditions of combination of wind speed and icing thickness are done. Through studies mentioned above, the following conclusions are obtained:

(1) Through simulation of strain segment model and one-tower-two-line model, results of these two models are found to be consistent. So it presents a relatively simple approach for positioning structurally weak point of the strain segment.

(2) Through simulation of strain segment model, the weak tower of strain segment is found, which provides technical support for anti-ice disaster.

(3) Under different conditions of wind speed and icing thickness combination, the weak tower is not fixed. The most dangerous tower does exist from the perspective of probability. Capacity to withstand loads of icing and wind in the different towers in strain segment are different.

(4) In the strain segment model, for the direction difference of wind load and icing load, with the increase of crossover wind speed, the corresponding crossover icing thickness of tower-line system would increase rather than decrease. In some conditions, it is structurally stable when the icing is thick. On the contrary, in the deicing process, with icing thickness decreasing, certain tower of the strain segment may have structure damage.

(5) Through simulation of strain segment model and one-tower-two-line model, weak point of the whole strain segment system can be positoned, which provides reliable basis for installation of stress monitoring device.

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